The HI Companions of HII Galaxies and Low Surface Brightness Dwarf Galaxies

Christopher L. Taylor

McMaster University
Department of Physics and Astronomy,
Hamilton, Ontario, Canada, L8S 4M1
taylorc@physun.physics.mcmaster.ca

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ABSTRACT

I study the VLA HI survey of HII galaxies by Taylor *et al.* (1995, ApJS, 99, 427; 1996, ApJS, 102, 189) and the VLA HI survey of low surface brightness (LSB) dwarf galaxies by Taylor *et al.* (1996, in press) to investigate the role of galaxy interactions in triggering the bursts of massive star formation seen in HII galaxies. Comparing the two surveys, I find that HII galaxies have companions more than twice as often as LSB dwarfs ($p = 0.57$ for HII galaxies, compared to $p = 0.24$ for LSB dwarfs). I examine the completeness of the companion samples detected by the two surveys. For the companions to HII galaxies, the sample is likely complete in the distribution of velocity separations from their parent galaxies, but is probably missing some companions at large projected linear separations because of the finite size of the VLA primary beam. For the companions of LSB dwarfs, the small number of detections means their distributions in velocity and linear separation are poorly determined, but the LSB dwarfs were observed with the same observational setup as the HII galaxies so they will have the same levels of completeness. Because the two samples were observed in exactly the same fashion, there will be no relative bias in the number of companions introduced in this way. In addition, the redshift distributions of the two samples are very similar, so there will not be a distance related relative bias.

Thus I conclude that the difference in the number of HI rich companions is genuine, and signifies a difference in the local, small scale environments between the two types of galaxy. I search through published galaxy catalogs to determine number of neighbors each galaxy has outside the area of the VLA observations. At these large separations, the number of neighbors is the same, within the errors, for the two types of galaxy. The high rate of companion occurrence at low separations for HII galaxies relative to LSB dwarfs supports the hypothesis that the bursts of star formation are triggered by galaxy interactions.

1. Introduction

The small scale environment of a galaxy can have a profound impact on that galaxy's evolution. Obviously mergers and tidal interactions can alter a galaxy's morphology by changing the distribution of its stars and gas. Interactions are also linked to nuclear star burst events, enhanced levels of massive star formation in galactic disks, and the formation of bars (*e.g.,* Bushouse 1987; Kennicutt *et al.* 1987; Noguchi 1987). All of these processes

are clearly most efficient in an environment of high galaxy density, where the likelihood for galaxies to interact is greatest. Even the type of galaxies available as interaction partners can be important, as shown by the examples of elliptical galaxies believed to have accreted gas from neighboring late type systems (*e.g.,* NGC 1052; van Gorkom *et al.* 1986).

Taylor, Brinks & Skillman (1993; hereafter TBS) used the idea that such interactions might trigger star formation to launch a program of searching for previously unknown companions. They selected a sample of nine dwarf galaxies currently experiencing a burst of star formation (HII galaxies), but without obvious interaction partners. If the bursts of star formation were related to interactions, then the companions must be optically faint to have avoided earlier detection. Dwarf galaxies were chosen because they are too small to sustain spiral density waves, which can trigger star formation episodes in spiral galaxies. TBS observed these HII galaxies with the NRAO[1] Very Large Array (VLA) in the 21 cm transition of HI, looking for optically faint but HI rich companions. They found four of the nine had previously unknown companions.

Following the success of the pilot study of TBS, Taylor *et al.* (1996a, 1995; hereafter TBGS) conducted a similar survey around a larger (N = 21), volume limited sample of HII galaxies, to put the result on a more solid statistical footing. They detected companions around 12/21 (= 0.57) HII galaxies. Taylor *et al.* (1996b, in press; hereafter TTBS) then surveyed a complementary sample (N = 17) of low surface brightness (*i.e.* non–starbursting) dwarf galaxies to serve as a control on the HII galaxy sample. TTBS found that only 4/17 (= 0.24) of the LSB dwarfs had HI-rich companions. Thus the HII galaxies are more than twice as likely to have HI rich companions as the LSB dwarfs.

The goal of this paper is to compare the data from these two HI surveys, to determine whether or not the presence of a nearby HI-rich companion can trigger bursts of star formation in low mass galaxies. In Section 2 I review the properties of the HII galaxy and LSB dwarf samples. In Section 3, in which I compare the completeness of the companion searches for the two surveys and discuss their observational biases. I will show that the difference in the observed numbers of companions is not caused by such effects. In Section 4 I compare the large scale (0.5 – 2.5 Mpc) environments of the two samples, showing that on average, on the *large scales*, the number of neighbors around the HII and LSB galaxies is the same. Section 5 is a discussion of the relationship between interactions and star formation in dwarf galaxies. Section 6 presents the conclusions.

Throughout this paper I adopt the following definitions: a companion to one of the HII

[1]The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

galaxies or LSB dwarfs means one of the objects detected in the VLA HI surveys described above, while a neighbor is a cataloged optical galaxy in the vicinity of one of the HII galaxies or LSB dwarfs. Note that there is a degree of overlap between these two classifications, as some of the companions are cataloged galaxies (*e.g.,* UM477A = NGC4116).

2. A Description of the Two Samples of Galaxies

The search for companions to HII galaxies is described in detail by TBGS. The sample of HII galaxies was selected from the galaxies studied by Salzer *et al.* (1989a,b). Because they originally come from an objective prism survey, these galaxies tend to have emission lines that are strong relative to their stellar continuum. Thus galaxies with inherently strong emission lines *or* a faint continuum are selected. The latter case can result in the inclusion of extremely low mass systems, while the former can include AGNs. In order to restrict the sample to relatively nearby dwarf galaxies, TBGS applied a velocity limit of $v_\odot \leq 2500$ km s^{-1} and an absolute magnitude limit of $M_B \geq -19$. Despite these selection criteria, two non-dwarfs – low luminosity spirals, were included in the sample. I will discuss the effects of these two galaxies on the results of this paper in Section 5.2. The HI masses of the HII galaxies range from a few $\times 10^7$ M$_\odot$ to a few $\times 10^9$ M$_\odot$. TBGS found that 12/21 of those HII galaxies had nearby companions rich in HI, for a measured companion frequency of 0.57, with a strong lower limit of 0.37. Because of the observational limitations (discussed in TBGS) it was not possible to derive a useful upper limit.

TTBS provide a detailed account of the search for companions to LSB dwarfs. The LSB dwarf galaxies were extracted from the list of low surface brightness galaxies studied by Bothun *et al.* (1993). To be included in the list used by Bothun *et al.* , a galaxy had to have a low central surface brightness and exceed a minimum radius. The lists of LSB galaxies are not statistically complete samples (*e.g.,* Schombert & Bothun 1988) and thus it is unknown how representative these galaxies are of whole LSB galaxy population. To obtain a sample useful for comparison with the HII galaxies, TTBS selected LSB dwarfs with a similar velocity limit (3000 km s^{-1}) and to resemble the HII galaxies in morphology, HI mass and HI linewidth. For example, the range in HI mass of the LSB dwarf galaxies is few $\times 10^7$ M$_\odot$ to a few $\times 10^9$ M$_\odot$, very similar to that of the HII galaxies. TTBS performed a Kolmogorov–Smirnov (K–S) test on the distribution of HI masses for the two samples and found the result consistent with the two samples coming from the same parent population. In the search for companions, TTBS found that only 4/17 (= 0.24) had HI-rich companions. Here again an upper limit was problematic.

It is important to distinguish between LSB and dwarf galaxies. The description “low

surface brightness" generally refers to the central surface brightness of a galaxy being below some limit usually set at about 23 magnitudes arcsec^{-2}. Dwarf galaxies often meet this criterion, although there are large numbers of LSB spiral galaxies (*e.g.,* Schombert *et al.* 1992). As described above, TTBS used selection criteria to obtain a sample of galaxies that are *both* LSB *and* dwarf, and the similarities in HI properties between their LSB dwarf sample and the HII galaxy sample shows they were successful.

The samples of HII galaxies and LSB dwarfs were selected to be as similar as possible, within the constraints of the source catalogs from which they were drawn. In addition, identical observational parameters were used in conducting each survey. These similarities reduce the prospect of one sample being biased toward having more companions relative to the other. As an example of the similarity between the two samples, Figure 1 shows histograms comparing their velocity distributions. Clearly the two are very similar, and the K–S test shows that the probability that the two distributions come from the same parent population is 0.98. In the next section I will examine the sources of a possible relative bias between the two samples and show that such a bias does not exist.

3. The Completeness of the Companion Samples

3.1. The Completeness in Radial Velocity Separations

The necessity of a finite number of channels and the desire for reasonable velocity resolution restrict the region of velocity space around each target galaxy that can be included in the HI surveys. This could lead to a bias in the observed distribution of radial velocity differences by excluding companions with high velocities relative to their parent galaxies. I will examine this distribution for the companions of both the HII galaxies and the LSB dwarf galaxies to investigate the possibility of this bias.

3.1.1. The Companions of the HII Galaxies

The upper panel of Figure 2 shows a histogram of the absolute value of radial velocity separations for the HII galaxy companions (solid line). The velocity coverage of the VLA observations is ± 250 km s^{-1}. Not a single HII galaxy / companion system has a separation greater than 110 km s^{-1}, despite the fact that the observable range is more than twice that. The dot-dash line shows the distribution for a random sample of velocity separations compiled by shuffling the radial velocities of all the HII galaxies and companions and forming random pairs (Turner 1976*b*). This represents what would be seen if there were

no true physical pairs and only random alignments in velocity space. The distribution of velocities towards low values is also consistent with a sample of true physical pairs, as false detections of companions resulting from noise spikes would be distributed randomly within the velocity coverage of the observations, not clustered toward low velocities.

The observed distribution falls off dramatically and approaches the limit of the random distribution by 110 $\mathrm{km\,s^{-1}}$. Studies of velocity distributions of paired galaxies been done by several authors for samples of binary galaxies drawn from catalogs which consist largely of "normal" galaxies (*i.e.* $M_B \leq -19$). Turner (1976*a*) found a cutoff for physically associated pairs at $\Delta v = 450$ $\mathrm{km\,s^{-1}}$, whereas Peterson (1979) adopted a value of 750 $\mathrm{km\,s^{-1}}$, and van Moorsel (1987) used 500 $\mathrm{km\,s^{-1}}$. The difference between the 110 $\mathrm{km\,s^{-1}}$ cutoff of the TBGS sample and the much large cutoff for the binary spiral samples reflects the differing mean mass of the HII galaxy sample compared to the "normal" galaxy samples. The escape velocity scales as the one-half power of the parent galaxy mass. The ratio of mean mass between the TBGS sample and that of Peterson is 40.8. Scaling 110 $\mathrm{km\,s^{-1}}$ up by $(40.8)^{1/2}$ gives 700 $\mathrm{km\,s^{-1}}$, very close to the cutoff velocity separation found by Peterson. Galaxies with more mass are able to retain companions with higher relative velocities.

Because the distribution of velocity separations falls off well before the end of the range of velocity coverage of the VLA, and because these counts seem to merge smoothly into the expected distribution of random background separations, I conclude that the sample of companions to HII galaxies is likely complete in velocity space.

3.1.2. The Companions of the LSB Dwarf Galaxies

Although the LSB dwarf galaxies have far fewer companions than the HII galaxies, the distribution of radial velocity separations shown in the lower panel of Figure 2 (solid line) does resemble the distribution of the HII galaxy companions in general shape. That is, the distribution peaks at low velocities and decreases at higher velocities. Unfortunately the small number of companions found around the LSB dwarfs makes it difficult to argue that distribution is truly similar to the distribution of HII galaxy companions. Like the HII galaxy companions, the largest velocity separation of the LSB dwarf companions is much lower than the maximum observable separation of 250 $\mathrm{km\,s^{-1}}$, but again, this could just be a result of the small number of detections. If the LSB dwarfs exist in an environment similar to the environments of the HII galaxies, the distributions of companions at large velocity differences will be similar as well. However, TTBS found that most of the companions to the LSB dwarfs were more massive galaxies, unlike the case for the HII galaxies, where the companions were of equal or less mass. Therefore, because the LSB dwarfs are bound to

more massive galaxies, their velocity separations could be larger than was true for the HII galaxies while still allowing the systems to be bound.

There is no evidence in the radial velocity distribution of companions to LSB dwarfs that there exist companions at large velocity separations. I conclude that I have not missed a large number of companions within one primary beam of the target galaxies due to the finite velocity coverage of the TTBS VLA observations.

3.2. The Completeness in Projected Physical Separation

The problem of assessing the completeness of the companion sample in spatial separation is entirely different from the problem of velocity separation. This is because the amount of velocity space observed by the VLA does not depend upon redshift, whereas for a constant angular size of the VLA primary beam, a larger physical area is imaged as the distance increases. It is immediately apparent that companions at relatively large projected separations may fall outside the primary beam for galaxies at smaller distances.

3.2.1. The Companions to the HII Galaxies

The ratio of the largest and smallest distances in the HII galaxy sample is 2.6, corresponding to a ratio of imaged areas of 6.8. The distribution of projected separations for the companion population of HII galaxies is shown in the upper panel of Figure 3. The vertical line in the Figure indicates the radius of the FWHM of the VLA primary beam for UM533, the closest HII galaxy. At least one of the distant HII galaxies has a companion beyond this radius, suggesting that some of the nearer galaxies could as well. Such companions would have been undetected by TBGS.

An additional effect adding to the incompleteness of the survey is the decrease in sensitivity of the VLA primary beam with distance from the pointing center. For observations in the 21–cm line, the sensitivity falls to half maximum at a radius of $15'$. The farther from the target galaxy a companion lies, the more HI it must have to be detectable. Figure 4 shows the distribution of angular separation for the companion population. The dashed vertical line shows the radius of the FWHM of the VLA primary beam. The mean HI mass of the four systems beyond the line is $18.5 \pm 4.4 \times 10^8$ M$_\odot$, while for the entire population it is $6.5 \pm 2.7 \times 10^8$ M$_\odot$, illustrating the effect of the decreasing sensitivity. For the companion with the widest angular separation in Figure 4 the decrease in sensitivity is approximately 0.17. A typical sensitivity for the distances of the HII galaxies is $\sim 3 \times 10^7$

M$_\odot$ (discussed in greater detail in the following section). For the widest separation, this limit becomes $\sim 2 \times 10^8$ M$_\odot$. Five companions have low enough HI masses to become undetectable at this separation, and even six of the HII galaxies would have been missed if they had been towards the edge of the primary beam. Clearly this effect could result in companions being missed in the survey.

Although it is likely that companions have been missed at large radii for the reasons discussed above, it is also possible that the true distribution of separations will tend towards companions with low separations, if the companions experience dynamical friction from dark matter halos in the HII galaxies (Lin & Tremaine 1983). For typical projected separations ($r = 60$ kpc) and radial velocities ($v = 40$ km s^{-1}), the crossing time is of order 6×10^9 yr. If the dark matter halos reach the distance of the companions and the companions are on circular orbits, then the timescale for dynamical friction can be written as:

$$t_{fric} = \frac{1 \times 10^{10}}{\ln \Lambda} \left(\frac{r}{60 \text{ kpc}} \right)^2 \left(\frac{v}{220 \text{ km/s}} \right) \left(\frac{2 \times 10^{10} \mathrm{M}_\odot}{M_{HII}} \right) \text{ yr}$$

where

$$\Lambda = \frac{r v^2}{G(M_{HII} + M_{comp})}$$

(Binney & Tremaine 1987).

For $M_{HII} = 10^9$ M$_\odot$ and $M_{comp} = 10^8$ M$_\odot$ this timescale is approximately 1.2×10^{10} yr. Thus the companions would have had plenty of time to experience dynamical friction, but not enough to have been swallowed by the HII galaxies yet. This time scale is, of course, lower limit because I have used observed orbital parameters like projected separations and radial velocities for the true separations and relative velocities.

The conclusion to be drawn regarding the completeness of the companion sample in physical separation is a fairly weak one. Because of the range in distance of the HII galaxies, and the fall off of sensitivity at the edges of the VLA primary beam, it is very likely that some companions have been missed. Unfortunately, because the distribution of the companions is unknown, the degree of incompleteness cannot be estimated.

3.2.2. The Companions of the LSB Dwarf Galaxies

The ratio of the largest and smallest distances in the LSB dwarf galaxy sample is 2.5, corresponding to a ratio of areas imaged of 6.3, nearly identical to the values for the HII galaxies. This is because the LSB dwarfs were chosen to span approximately the same range in redshift as the HII galaxies (recall Figure 1).

The distribution of projected separations for the companion population of LSB dwarfs is shown in the lower panel of Figure 3. The vertical line indicates the radius of the FWHM of the VLA primary beam at the distance of the closest galaxy in the LSB sample. The companions of the LSB dwarfs are, on average, further away from the LSBs than the companions of HII galaxies are from the HII galaxies. This may, however, be a function of the small number of detected companions. It is also possible that because the companions to LSBs are mostly more massive galaxies the LSB/companion systems can remain bound to larger distances for roughly equivalent velocity separations.

Even less can be said about the completeness in spatial separation of the LSB dwarf sample than could be about that of the HII galaxies. If it is true that the companions of LSB dwarfs tend to larger physical separations, then the LSB dwarf sample is likely *more* incomplete in the companion count than is the the HII galaxy sample. In this case, the variation of sensitivity of the VLA primary beam with radius will affect the LSB dwarf sample more than it does the HII galaxy sample. However, if the distribution seen in Figure 3 is just the result of a small sample size, then the level of incompleteness is likely the same as for the HII galaxies, in which case the primary beam effect will be the same on both samples. Thus *either* :

1. the companions to LSB dwarfs are distributed at larger linear separations than are the companions of HII galaxies, in which case the incompleteness in the companion counts is greater than for the HII galaxies; *or*

2. the two distributions are roughly similar, in which case the incompleteness of the two samples is roughly the same.

Based on the current data there is no way of determining which of these possibilities is correct.

3.3. Sensitivity Limits to Detectable Masses of HI Companions

Another way in which companions might be missed by TBGS or TTBS is if they do not have enough HI to be detected. This is especially acute for dwarf ellipticals, as dEs have very little or no HI, but it will also affect the detection of low mass dwarf irregulars (see the discussion below).

3.3.1. The Companions of the HII Galaxies

Regarding dwarf elliptical as companions, I simply note that only one candidate was seen in any of the optical data (see UM465 in TBGS), although the area of the CCD on the sky was much smaller than the area of the HI data. I will discuss a search for optical companions performed using the Center for Astrophysics (CfA) redshift survey in Section 4.

The upper panel of Figure 5 shows HI masses for the sample of *both* HII galaxies and companions, plotted as a function of redshift (distance) . The solid line shows the sensitivity of the TBGS observations with distance for an unresolved point source with a typical single channel noise of 1.3 mJy beam^{-1}. The lower envelope of HI mass of the combined sample is roughly constant with distance, at a few times 10^7 M$_\odot$, even at small distances where the detection threshold is significantly lower. The only point below this constant level corresponds to the HII galaxy UM 538, at a distance of 14.3 Mpc. It is the only galaxy *or* companion that could possibly have been lost if it were at a higher redshift within the limits of the survey. I take this as an indication that there are not large numbers of companions of HI mass $\sim 10^7$ M$_\odot$ missing from the sample at the larger distances. This is a result of the relatively narrow range in velocity covered by the HII galaxies (from 700 km s^{-1} to 2500 km s^{-1}). On the other hand, there are a number of dwarf irregular galaxies in and around the Local Group with HI masses in the range $\sim 10^6$ to 10^7 M$_\odot$ (*e.g.,* Leo A, Sag DIG, GR 8; Lo, Sargent & Young 1993). Such objects are not limited to the Local Group (Côté 1995), so there could be a significant population of companions at low HI mass (of order 10^6 M$_\odot$ or less) which would remain undetected unless closer HII galaxies were surveyed, or else a factor of 100 more integration time is spent on the current sample.

3.3.2. The Companions of the LSB Dwarf Galaxies

TTBS obtained optical images of each of the LSB dwarfs using the STScI Digitized Sky Survey. None of the systems had a potential dwarf elliptical companion visible in the images, though the images were restricted to a small region around each galaxy ($\sim 7.5'$).

A plot of HI mass versus distance for the LSB dwarfs and their companions is shown in the lower panel of Figure 5. The detection limit is nearly identical to the limit for the HII galaxy observations, being slightly lower because most of the LSB dwarf observations took place after sunset, whereas nearly all of the HII galaxy took place during the day and close to the solar maximum. Thus the LSB dwarf observations are less affected by solar interference, although they are not unaffected (TTBS).

As was true for the HII galaxies and their companions, the detections of LSB dwarfs and their companions do not approach the detection limit, suggesting that there are not large numbers of objects hiding below the detection threshold.

3.4. Summary of the Two Samples' Completeness

In the above subsections it was shown that the HII galaxy companion sample is likely complete in the distribution of radial velocity separations. Although there are not enough detections of companions around LSB dwarfs to show this is also true for that sample, the similarity of both the target galaxies' properties and the observing conditions makes it highly likely. It was also shown that the HII galaxy companion sample is likely incomplete in projected linear separation, in the sense of missing companions around the most nearby HII galaxies at separations greater than ~ 100 Mpc. Because the LSB dwarfs have approximately the same distribution in redshift, this is likely true for them as well. Finally it was argued that the two samples are not likely to be missing large numbers of companions at the sensitivity level of the observations ($\sim 10^7$ $M_\odot$), although the data do not constrain the number of less massive companions. In any event, the sensitivity of the two surveys to HI mass is nearly identical, so the effects of this sensitivity limit will be the same on each sample.

The most important fact to keep in mind for this work is the great similarity between the two surveys being studied, in terms of the redshift distributions, galaxy masses and observing setups. Because of this, whatever biases imposed due to limitations in the samples (*e.g.,* the projected linear separation) will affect both the HII galaxy and LSB dwarf samples equally. Therefore the difference between the companion rates of the two types of galaxy noted in Section 1 and by TTBS is real, and not caused by a relative bias between the samples.

4. A Comparison of the Large Scale Environments of HII and Low Surface Brightness Dwarf galaxies

The previous section showed that the difference in the number of HI companions around LSB dwarf and HII galaxies is not due to selection effects effects inherent in galaxy samples, nor is it due to limitations imposed by the observing conditions or setup. The observed difference in the number of companions therefore reflects a true difference in the small scale environment of the two populations. However, it is likely that the small scale environment is influenced by the larger scale environment (*e.g.,* cluster versus field, or supercluster versus void). If, to give an extreme example, all the HII galaxies were found to be in the center of the Virgo Cluster, while all the LSB dwarfs were on the edge of a void, then the observation that HII galaxies have more companions would be a reflection of the generally denser environment of the particular sample of HII galaxies and not necessarily indicating an important difference in their evolution. On the other hand, if the two types of galaxy were found to have the same large scale environment, then the difference in the companion rates would be significant.

To investigate the large scale environments of the two samples in I will compare them to two galaxy catalogs: the CfA redshift survey catalog (Huchra *et al.* 1983) and the Nearby Galaxies Catalog (Tully 1988).

4.1. Comparison to the CfA Redshift Survey

The area of overlap of the CfA redshift survey with the TBGS and TTBS is in two regions, $b_{II} \geq 40°$, $\delta \geq 0°$ and $b_{II} \leq -30°$, $\delta \geq 2°.5$. In these areas the catalog is complete to $B \leq 14.5$ (Huchra *et al.* 1983). For the most and least distant galaxies in the two samples, this corresponds to $M \leq -18.4$ and $M \leq -15.5$ respectively. Only for the closest galaxies will any of the neighbors be dwarfs. A comparison with primarily massive galaxies will still be useful, because dwarf galaxies are known to trace the same structures as bright galaxies (*e.g.,* Thuan *et al.* 1991)

These areas contain 11/21 of the HII galaxies, and 15/17 of the LSB dwarfs. I obtained the catalog from the Astrophysics Data Service (ADS) Catalog Query Service available on the World Wide Web. I searched through the catalog looking for neighbors around each galaxy with velocities within 500 $\mathrm{km\,s^{-1}}$ of the target galaxy. The choice of 500 $\mathrm{km\,s^{-1}}$ as the velocity limit was not based on any physical reasons, but rather to allow for easy comparisons with similar studies by Bothun *et al.* (1993) and Campos–Aguilar & Moles (1991) which adopted that limit. Note that 500 $\mathrm{km\,s^{-1}}$ is consistent with the typical

velocity limits for samples of binary spirals discussed in section 2.1.

The counts were binned in 0.5 Mpc bins running from 0 to 2.5 Mpc. Figure 6 shows the mean neighbor counts plotted versus distance for the HII galaxy (triangles) and LSB dwarf galaxy (circles), with associated error bars. The open symbols show the counts in each bin, while the filled points show the cumulative values. In all bins the counts per bin are the same within the errors, although in the last two bins (2 and 2.5 Mpc) the LSB dwarf neighbor counts begin to diverge from the HII galaxy neighbor counts. It is possible that if the samples were larger (and thus the errors smaller) that there might be a significant difference. The counts at smaller radii, however, are nearly identical, suggesting that the members of the two samples are in environments of similar galaxy density. From neighbor counts using the CfA redshift survey catalog, I conclude that, on average, the HII galaxies and LSB dwarfs are found in environments of similar galaxy density on scales larger than the VLA primary beam (*i.e.,* $\sim$ 250 kpc).

How does this result compare with other studies of galaxy environments? Bothun *et al.* (1993) have done a very similar analysis on much larger samples (N between 135 and 870) for galaxies in the redshift range 2000 – 12000 $\mathrm{km\,s^{-1}}$. Most of the galaxies from that work are not dwarfs like the galaxies of this study, but rather are more massive spirals and ellipticals, with large HI line widths. For the portion of the Bothun *et al.* (1993) sample cataloged by Schombert *et al.* (1992), the mean HI line width measured at half the maximum intensity is 147 ± 8 $\mathrm{km\,s^{-1}}$, while for the LSB dwarf sample of TTBS the line width measured at zero intensity is only 107 ± 8 $\mathrm{km\,s^{-1}}$. If the LSB dwarfs had been measured on the half–maximum too the line widths would be even smaller, emphasizing even more the difference between the Bothun *et al.* and the TTBS LSB samples.

Bothun *et al.* (1993) searched for neighbors within a projected radius of 2.4 Mpc and $\pm$ 500 $\mathrm{km\,s^{-1}}$ of each of their sample galaxies. They binned their neighbor counts in 0.5 Mpc bins, finding that at every bin the cumulative number of neighbors for HSB galaxies was larger than for LSB galaxies. The difference was most pronounced for the 0 – 0.5 Mpc bin. This is consistent with my VLA result that in the range of distances 0 – 0.25 Mpc HII galaxies have more HI companions than do LSB dwarfs. In my neighbor counts using the CfA redshift survey, however, I find that the HII galaxies and the LSB dwarfs have the same number of neighbors at *all* separations within the errors, although the counts do seem to be diverging from each other at larger radii. Thus based only on the neighbor counts from optical catalogs, my results would not agree with the Bothun *et al.* result, but this may simply be because I have far fewer galaxies in my samples than they had, resulting in larger error bars. The Bothun *et al.* samples have from 7 to 50 times as many galaxy as the samples of this paper. When including the VLA discovered companions, I

find the HII galaxies have an excess of companions in the 0 – 0.25 Mpc range, but most of these companions are not bright enough to be in the catalogs searched by Bothun *et al.* (1993). Thus within the errors of the neighbor counts, there is no significant difference in the environments of the two samples on the scales of 0.5 to 2.5 Mpc. Overall, I find that LSB dwarfs have fewer companions at short radii than do HII galaxies, but at larger radii the two sample have similar numbers of (optical) neighbors. This is the same result arrived at by Bothun *et al.* for their samples of LSB and HSB galaxies.

Other studies have investigated the environments of HII galaxies, but unlike my study and that of Bothun *et al.* (1993), they did not compare HSB and LSB systems. Work by Campos–Aguilar & Moles (1991), Campos–Aguilar *et al.* (1993) and Telles & Terlevich (1995) has found that HII galaxies tend to be isolated from luminous, massive galaxies. These authors used various optical galaxy catalogs to search for bright neighbors. Typically from one-third to three-fourths of the HII galaxies were found to be isolated, with isolation criteria of 1 Mpc and $\pm$ 500 km s^{-1}. By restricting themselves to magnitude limited optical catalogs, however, these authors could not have found the faint dwarfs that form the majority of the optical counterparts to the TBGS HI detections.

For a quantitative comparison, 19 out of 21 HII galaxies from the TBGS sample are also included in the Campos–Aguilar & Moles (1991) sample. If we consider these 19 HII galaxies then using just the Campos–Aguilar & Moles (1991) detections of neighbors, the fraction of isolated galaxies is 0.11. The fraction of isolated HII galaxies for their entire sample is much higher, 0.33. With such a high fraction of isolated HII galaxies in their sample they argue that galaxy interactions are not responsible for the bursts in *all* HII galaxies.

This difference between the 0.11 and 0.33 fractions occurs because the TBGS sample has been restricted to less than 2,500 km s^{-1}. All these galaxies lie within the Local Supercluster, whereas the much larger sample of Campos–Aguilar & Moles (1991) contains galaxies of velocity up to $\sim$ 15,000 km s^{-1} and in a variety of large scale environments. In fact, Campos–Aguilar *et al.* (1993) do find that the mean redshift of HII galaxies without neighbors is higher than that of those with companions. They suggest this is because the CfA redshift survey, which they use to search for companions, is magnitude limited, making faint neighbors at higher redshifts more difficult to detect. It is likely, therefore, that a VLA HI survey of the entire Campos–Aguilar & Moles (1991) sample would yield a higher fraction of galaxies with interaction partners than is currently known.

4.2. Comparison to the Nearby Galaxies Catalog

As mentioned previously, the CfA survey does not have complete coverage over the area of all the galaxies in the HII galaxy and LSB dwarf samples. Because of this I could only compare the parts of those samples that did overlap with the CfA coverage. The sample in the Nearby Galaxies Catalog (hereafter NBG; Tully 1988), however, has nearly uniform coverage across the entire sky (except what is obscured by the Galactic plane). This catalog has roughly the same number of galaxies as the portion of the CfA survey used above, but distributed across the entire sky. Therefore the limiting magnitude is not as deep. Rather than compute projected separations with the somewhat sparsely distributed galaxies in the NBG, I will compare the positions and velocities of the sample galaxies with the positions and velocities of the groups defined in the Catalog. For this purpose I defined a sample from the Catalog that contained all galaxies within three degrees and 500 $\mathrm{km\,s^{-1}}$ of a galaxy in either the HII galaxy or LSB dwarf samples.

An HII galaxy or LSB dwarf was considered to be a group member if it met both the following criteria:

1. Its projected separation from the group center had to be less than twice the mean of the separations of each pair formed by pairing each group member with every other group member, and;

2. Its velocity had to be within two sigma of the group mean velocity, where one sigma was the velocity dispersion of the group.

This is a conservative definition, but one which is unlikely falsely call one of the sample galaxies a group member. To test how well this definition works, I applied it to the NBG sample defined above, to see whether or not known group members would be wrongly excluded. Out of 32 groups with 131 members, only two galaxies (1.5%) would have been excluded by my criteria. Thus it is unlikely that I have incorrectly labeled an HII or an LSB galaxy as not being a member of any group. However, if incorrect assignments occur, they should happen with equal frequency to both samples, *assuming* the groups near the different samples are similar to each other. To check the validity of this assumption, I calculated the separation of each pair in every group in the NBG sample. The mean of this pairwise separation within groups near HII galaxies is 0.48 ± 0.10 Mpc, and 0.50 ± 0.05 Mpc for groups near LSB dwarfs. There is no evidence groups near HII galaxies are different than groups near LSB dwarfs.

Using the above conservative definition of group membership, I searched through the groups in the NBG sample, checking for any to which an HII galaxy or LSB dwarf might

belong. I find that 5 out of 21 (= 0.24) HII galaxies belonged to groups, while 7 of 17 (= 0.41) of the LSB dwarfs did. Following TBS and TBGS I can use the binomial distribution to calculate upper and lower limits on these fractions. Using this method to determine, for example, the lower limit for the number of HII galaxies in groups, will yield the lowest fraction of HII galaxies in groups which is consistent with observing 5 out of 21 at least five percent of the time if the experiment were repeated many times. With these calculations, the fraction of HII galaxies in groups is $0.24^{+0.20}_{-0.14}$ and the fraction of LSB dwarfs in groups is $0.41^{+0.23}_{-0.20}$. These fractions are within the uncertainties of each other, indicating that there is no significant difference between the group environments of the LSB dwarfs and the HII galaxies.

4.3. Contamination from the Virgo Cluster

Nineteen of the twenty–one HII galaxies from TBGS lie in an area of the sky on the periphery of the Virgo Cluster. All of these nineteen are within 30° of the cluster center. Thus there is the possibility that some of the HII galaxy – companion pairs are not physically associated, but caused by a chance occurrence between a cluster member and a nonmember at similar velocities.

To assess this possibility I will use the data of the Virgo Cluster study by Binggeli, Tammann & Sandage (1987; hereafter BTS). According to BTS, the Virgo Cluster contains several distinct substructures. Cluster A, centered on M87, and Cluster B, centered on M49 are the two largest units, together containing most of the galaxies. The surface density of number counts for late–type galaxies can be described with an exponential profile: $I(r) = I_0 \exp(r/r_0)$, where $I_0 = 5$ arcsec^{-2} and $r_0 = 3.3$ degrees. Taking r to be the angular distance of each HII galaxy from the center of Cluster A ($12^h\ 25^m$, $13^\circ\ 0'$), this expression yields the number of Virgo galaxies expected within a VLA primary beam which is pointed at each HII galaxy. I then determine the fraction of Virgo galaxies which have velocities within $\pm$ 250 km s^{-1} of each HII galaxy to estimate the probability that if a galaxy did fall within the VLA primary beam, it would also be in the correct velocity range so that TBGS would detect it. Thus I obtain for each observation of an HII galaxy the number of members of Cluster A expected to be detected. Summing this over all the HII galaxies, only 0.16 galaxies are expected to contaminate the experiment. Thus it is likely that no members of Cluster A are contaminating the experiment.

BTS did not derive a radial profile from the number counts of Cluster B, presumably because it is not symmetric. However, it lies closer ($12^h\ 25^m.8$, $8^\circ\ 51'$) to the TBGS HII galaxies than does Cluster A, so some measure of the possible contamination is desirable.

BTS found that Cluster B has one–fifth the population of Cluster A. To get a rough idea of the possible contamination caused by Cluster B, I will assume an exponential distribution as per Cluster A, with the same scale length, but total number of galaxies scaled down by a factor of five. Repeating the calculation done for Cluster A, shows that the number of contaminating galaxies is 0.09, less than one, and less than what is expected from Cluster A. I therefore conclude that interlopers from the Virgo Cluster are not likely affecting the counts of companions.

Only eight of sixteen LSB dwarf galaxies from TTBS are within 30° of the cluster center, but some of these LSB dwarfs are closer to the center than any of the HII galaxies. Repeating the calculations above for the LSB dwarfs, I find the number of contaminating galaxies to be expected is 0.41. This is somewhat larger than for the HII galaxies, but still so small as to make it unlikely. However, if one of the HI companions found by TTBS is in fact a chance alignment and not a physical pair, then removing it from the sample would make the companion rate even lower than 0.24 and increase difference between HII galaxies and LSB dwarfs.

5. Discussion

5.1. Interaction Triggered Star Formation in Dwarf Galaxies

By comparing the data from TBGS and TTBS I have shown that HII galaxies have more HI–rich companions than do LSB dwarfs. The fraction of HII galaxies found to have such companions is 0.57, with a lower limit of 0.37 (TBGS). The fraction of LSB dwarfs that have companions is 0.24, with a lower limit of 0.08 (TTBS). In the previous sections I showed that this difference is real, not caused by observational biases, selection effects, or differences in the large scale environments of the two samples.

Because HII galaxies are currently experiencing bursts of massive star formation while LSB dwarfs have relatively low star formation rates, I interprete the difference in companion rates between the two types as evidence that interactions with such companions can trigger bursts of star formation. This interpretation suggests that HII galaxies may be LSB dwarfs in which interactions have lead to a burst of star formation. The similarities in the global properties of HII galaxies and LSB dwarfs (*e.g.* HI mass, HI line width) are consistent with this, although larger and more complete samples (especially for the LSB dwarfs) should be studied to confirm this idea.

Taylor *et al.* (1994) suggested a possible physical mechanism by which companions could trigger bursts of star formation in HII galaxies. It was proposed that the interaction

drove gas to the center of the galaxy, where it accumulated until some physical condition (such as rising above a threshold surface density) was met, and a burst of star formation began. Radial inflows of gas have been seen to occur in numerical models of interacting galaxies (*e.g.,* Noguchi 1987, 1988; Hernquist 1989; Mihos & Hernquist 1994). Many, but not all, of the HII galaxies have their star formation bursts occuring at the center of the galaxy (Salzer *et al.* *et al.* (1989b), therefore some alternate mechanism is needed to explain the off–center systems.

Under the Taylor *et al.* (1994) scenario, LSB dwarfs should have HI distributions where the surface central density of HI is lower than in HII galaxies. It is known that the total surface density of LSB galaxies in general is less than for HSB systems (*e.g.* McGaugh 1996). To explore any relationship between the HII galaxies and the LSB dwarfs will require high resolution observations to compare their HI distributions, kinematics and rotation curves. Some of the necessary data have already been obtained. LSB galaxies are usually dominated by their dark matter components (Zwaan *et al.* 1995), a situation which would tend to make them stable against global perturbations which could trigger star formation bursts. This stability could play a role in determining which LSB dwarfs become HII galaxies and which do not, although some HII galaxies are also known to be dark matter dominated (*e.g.* NGC 2915; Meurer *et al.* 1996), so clearly dark matter cannot always provide enough stability to prevent a star formation burst. There is a lack in the literature of computer simulations of dwarf galaxy encounters that might shed some light on the role of dark matter and what sorts of dwarf–dwarf encounters are necessary dynamically to lead to the kind of interaction described by Taylor *et al.* (1994).

The result of this paper suggests that interactions play an important part in triggering bursts of star formation in HII galaxies. However, interactions cannot be the only mechanism at work because in the sample of TBGS 9/21 HII galaxies had no detected companions. In section 3.2.1 I showed that there were likely companions missing from the TBGS survey at large radii from the HII galaxies, but I could not determine the extent of this incompleteness. It is possible that some HII galaxies have no companions, in which case some other mechanism would be responsible for the bursts of star formation. It is also apparent that the mere presence of a companion to interact with is not sufficient to trigger a burst of star formation because 4/17 LSB dwarfs have companions but no bursts. This could be explained if LSB dwarfs were *more* dark matter dominated than HII galaxies, but questions of how much dark matter is needed to stabilize against interactions of any given strength are best sorted out by numerical simulations which explore the parameter spaces relevant to encounters among dwarf galaxies.

5.2. Caveats

There are two items which could cloud the relatively straightforward interpretation discussed above. The first concerns two of the galaxies in the HII galaxy sample. As discussed by TBGS, two of the HII galaxies are in fact small spirals (UM477 and UM499) and not dwarf galaxies. They were retained in the analysis because they have bursts of star formation in their nuclei (Salzer *et al.* 1989*b*), and the goal of the study is to investigate a possible connection between bursts and galaxy interactions. Dwarf galaxies are excellent for such a study because they are less complex systems than spirals and do not have spiral density waves which can also serve as a star formation trigger. Thus by including two spirals in the sample, I am possibly adding two galaxies to the sample which may not belong there. I feel justified in including the two spirals because their bursts are at the galaxy centers, where the rotation curve shows solid body rotation. Thus the centers of these galaxies have physical conditions similar to the other HII galaxies (Taylor *et al.* (1993), TBGS). However, I note that if the two spiral galaxies are excluded from the sample, the companion rate becomes $10/19 = 0.53$, with a lower limit of 0.32. This is compared to $12/21 = 0.57$, with a lower limit of 0.37. Thus the companion rate decreases, but the lower limit is still above the companion rate measured for the LSB dwarfs (0.24).

The second item concerns the sample of LSB dwarfs. Because of the difficulties inherent in identifying LSB galaxies (Disney & Phillipps 1983) no complete samples exist. This is true of the source lists from which TTBS drew their sample of LSB dwarfs (*e.g.,* Schombert *et al.* 1992). Thus it is difficult to quantitatively characterize the LSB dwarf sample. One example of how this can lead to trouble is the case of LSB dwarf L1-137 and its HI–rich companion, L1-137A. Inspection of digitized POSS images found that the companion has a faint, low surface brightness optical counterpart, one which was not included in the original source list of LSB dwarfs. If this galaxy had been included in the original sample of LSB dwarfs, then both L1-137 and L1-137A would be considered as companions to LSB dwarfs (in a binary pair) and the companion rate would be $5/18 = 0.28$, instead of $4/17 = 0.24$. Because the LSB sample is incomplete I cannot estimate how many more binary LSB dwarf systems there are where not even one member made the TTBS sample. The L1-137 system is the only such case found by TTBS, and would make a small change in the companion rate, but it does amply illustrate the need for both larger samples and more complete samples (or at least samples with better quantified incompleteness). The best solution to this problem would be a highly sensitive HI mapping survey over a relatively large ($\sim$ 300 degrees^2). Such a survey would have similar sensitivities to both LSB dwarfs and HII galaxies, which could be distinguished from each other in follow–up optical work.

6. Conclusions

I have used HI surveys of HII galaxies (Taylor *et al.* 1995; Taylor *et al.* 1996) and LSB dwarf galaxies (Taylor *et al.* 1996b) to study the relationship between galaxy environment and bursts of star formation in dwarf galaxies. The primary result of this work is:

1. HII galaxies have a rate of companion occurrence more than twice as high as do LSB dwarfs (0.57 compared to 0.24). The lower limit on the companion frequency for HII galaxies is 0.37, still higher than the observed rate for LSB dwarfs. Because of the incompleteness in projected separation from the parent galaxy that affects the companion samples, upper limits are impossible to determine. However, I have shown that this incompleteness will affect both samples in the same way, and will not cause a relative bias between them. Thus I conclude that this difference in the companion frequency is genuine.

This is supported by the following results:

2. The distribution of companions to HII galaxies detected by Taylor *et al.* (1995; 1996a) is likely complete in velocity separation from the HII galaxy. It is unlikely that any physically associated companions were missed because they were outside the velocity coverage of the observations. The distribution of companions to LSB dwarfs detected by Taylor *et al.* (1996b) is not well determined due to the small number of objects detected. However, because the LSB dwarfs have dynamical masses similar to the HII galaxies, and were observed in exactly the same fashion as the HII galaxies, their distribution is likely complete as well.
3. The distribution of companions to HII galaxies is likely *not* complete in projected linear separation. This is because the fixed angular size of the VLA primary beam images larger areas as the distance of the target galaxy increases. Taylor *et al.* (1995; 1996a) detected companions around the most distant HII galaxies that were so far from their parent galaxies that they would not have been seen around the closest HII galaxies. Without knowing in an unbiased fashion how the companions are distributed with respect to their parent galaxies, the incompleteness due to this effect cannot be estimated. Similarly the distribution of companions to LSB dwarfs is likely not complete in projected linear separation.
4. The lower limit HI sensitivity of the two surveys is approximately a few $\times$ 10^7 $M_\odot$ over most of the distance range of the two samples. The samples of companions are

not likely missing objects down to this level of sensitivity, though there could be objects less massive than this that remain undetected.

5. The large scale environments (out to separations of 2.5 Mpc) of the HII galaxies and the LSB dwarfs are very similar, based on searches for nearby neighbors and groups in published galaxy catalogs. Within the errors, the distribution of neighbor separations for HII galaxies and LSB dwarfs is the same. Also, there is no significant difference in the fraction of HII galaxies and LSB dwarfs which belong to galaxy groups.

The high rate of companion occurrence for HII galaxies relative to LSB dwarfs supports the hypothesis that interactions can trigger the bursts of star formation seen in HII galaxies. This implies that HII galaxies may be LSB dwarfs in which a burst of star formation has occured, but more evidence is needed to confirm this idea. The data in the two surveys do not suggest by what mechanism star formation bursts can be triggered, although Taylor *et al.* (1994) do offer one possibility.

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Fig. 1.— Upper: A histogram showing the distribution of recession velocities for the sample of HII galaxies. Lower: A histogram showing the distribution of recession velocities for the sample of LSB dwarfs.

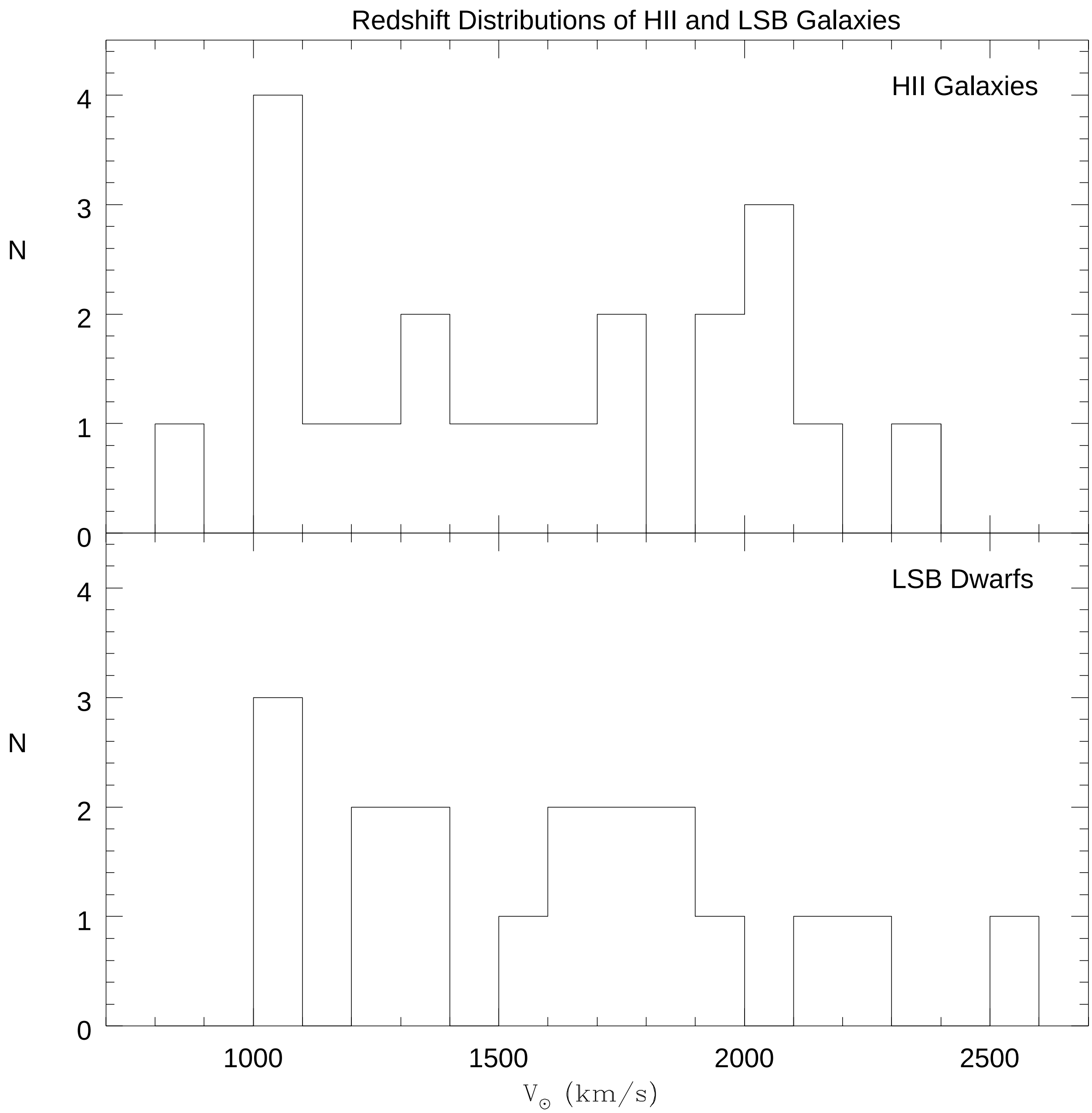
Fig. 2.— Upper: The bold face histogram shows the distribution of velocity separations of the companions from their parent HII galaxies. The shaded histogram is a sample made by randomly selecting HII galaxies and companions and computing the velocity difference. Lower: The bold face histogram shows the distribution of velocity separations of the companions from their parent LSB dwarf galaxies. The shaded histogram is a sample made by randomly selecting LSB dwarfs and companions and computing the velocity difference.

Fig. 3.— Upper: A histogram of the distribution of projected linear separations of the companions from their parent HII galaxies. The vertical lines shows the edge of the $30'$ VLA primary beam at the distance of the closest HII galaxy. Lower: A histogram of the distribution of projected linear separations of the companions from their parent LSB dwarf galaxies. The vertical lines shows the edge of the $30'$ VLA primary beam at the distance of the closest LSB dwarf.

Fig. 4.— A histogram of the distribution of angular separations of the companions from their parent HII galaxies. The dashed line shows the radius FWHM of the VLA primary beam.

Fig. 5.— Upper: A plot of HI mass versus v_{corr} for the HII galaxies (open triangles) and their companions (y–shaped symbols). The curve shows the HI sensitivity as a function of distance for a typical observation. Lower: A plot of HI mass versus v_{corr} for the LSB dwarfs (open circles) and their companions (stars). The curve shows the HI sensitivity as a function of distance for a typical observation.

Fig. 6.— The mean number of neighbors in 0.5 Mpc wide bins versus separation from the sample galaxies. The open symbols show the mean counts in each bin, while solid symbols show cumulative mean counts. The dashed vertical line shows the maximum separation from a galaxy observable with one pointing of the VLA.



Redshift Distributions of HII and LSB Galaxies
HII Galaxies
LSB Dwarfs
N
N
0
1
2
3
4
1000
1500
2000
2500
V$_\odot$ (km/s)

Figure 1

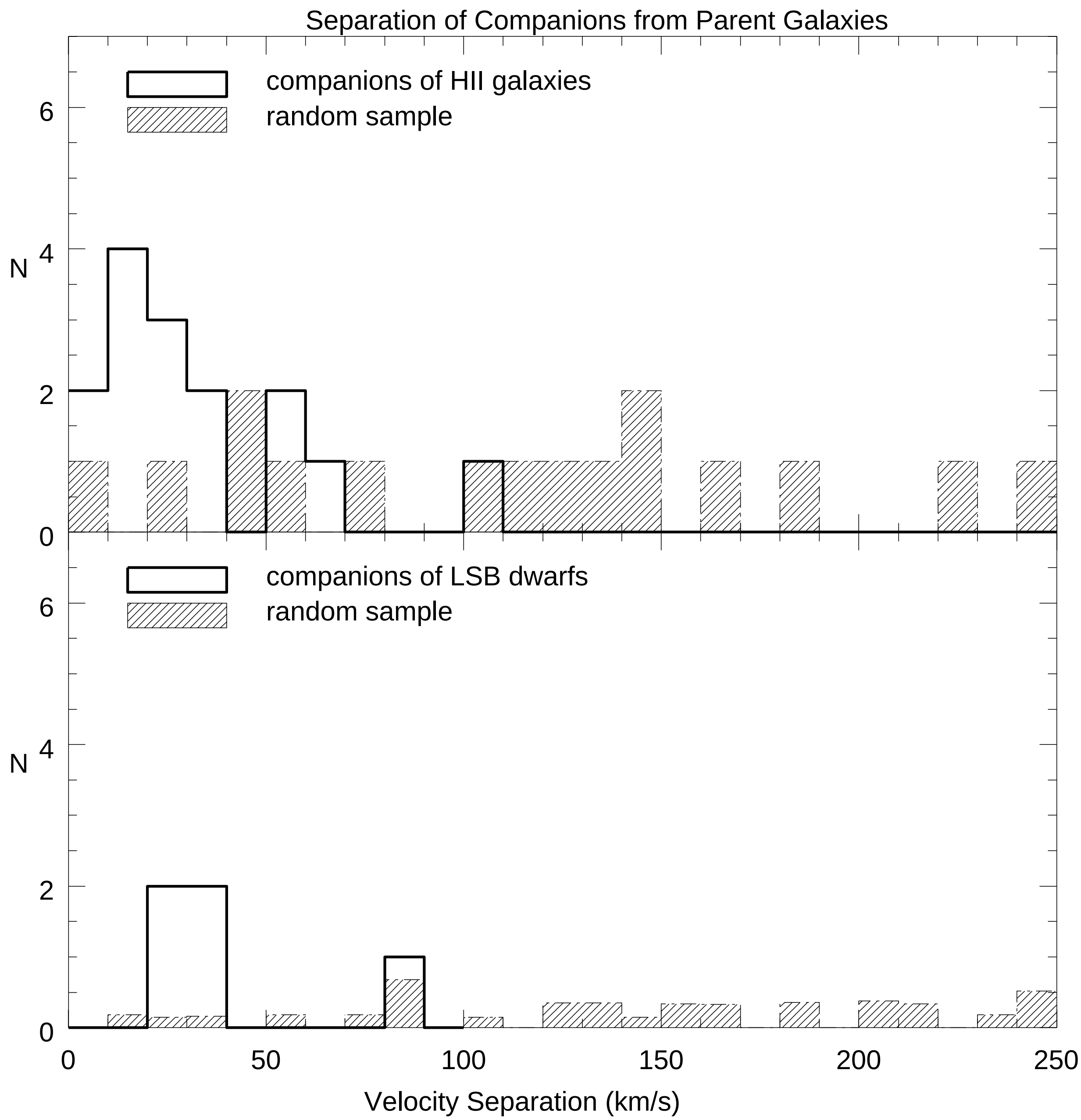

Separation of Companions from Parent Galaxies
companions of HII galaxies
random sample
companions of LSB dwarfs
random sample
N
N
0
2
4
6
0
50
100
150
200
250
Velocity Separation (km/s)

Figure 2

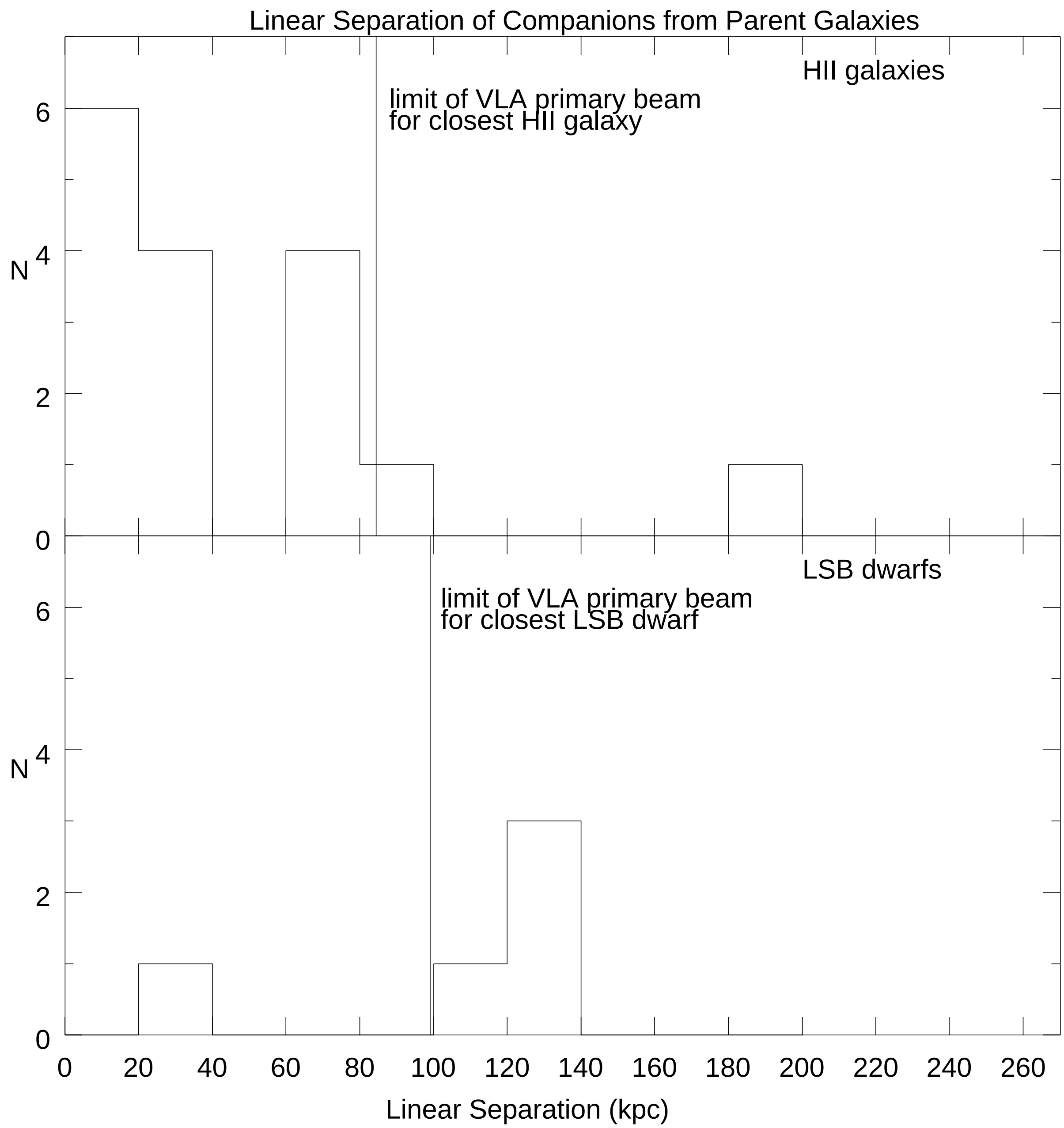

Linear Separation of Companions from Parent Galaxies
HII galaxies
limit of VLA primary beam
for closest HII galaxy
LSB dwarfs
limit of VLA primary beam
for closest LSB dwarf
N
N
0
2
4
6
0
20
40
60
80
100
120
140
160
180
200
220
240
260
Linear Separation (kpc)

Figure 3

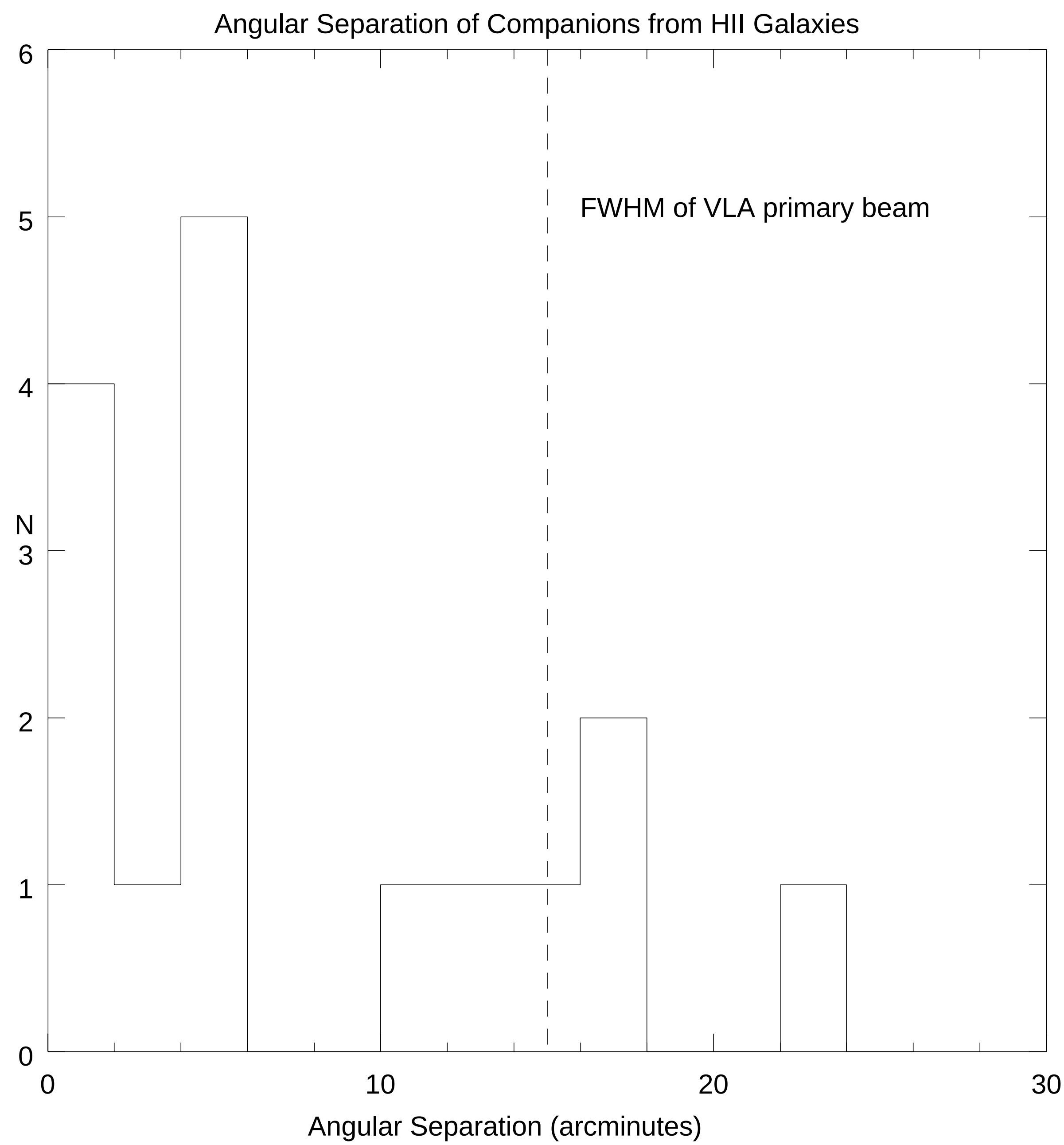

Angular Separation of Companions from HII Galaxies
FWHM of VLA primary beam
N
0
1
2
3
4
5
6
0
10
20
30
Angular Separation (arcminutes)

Figure 4

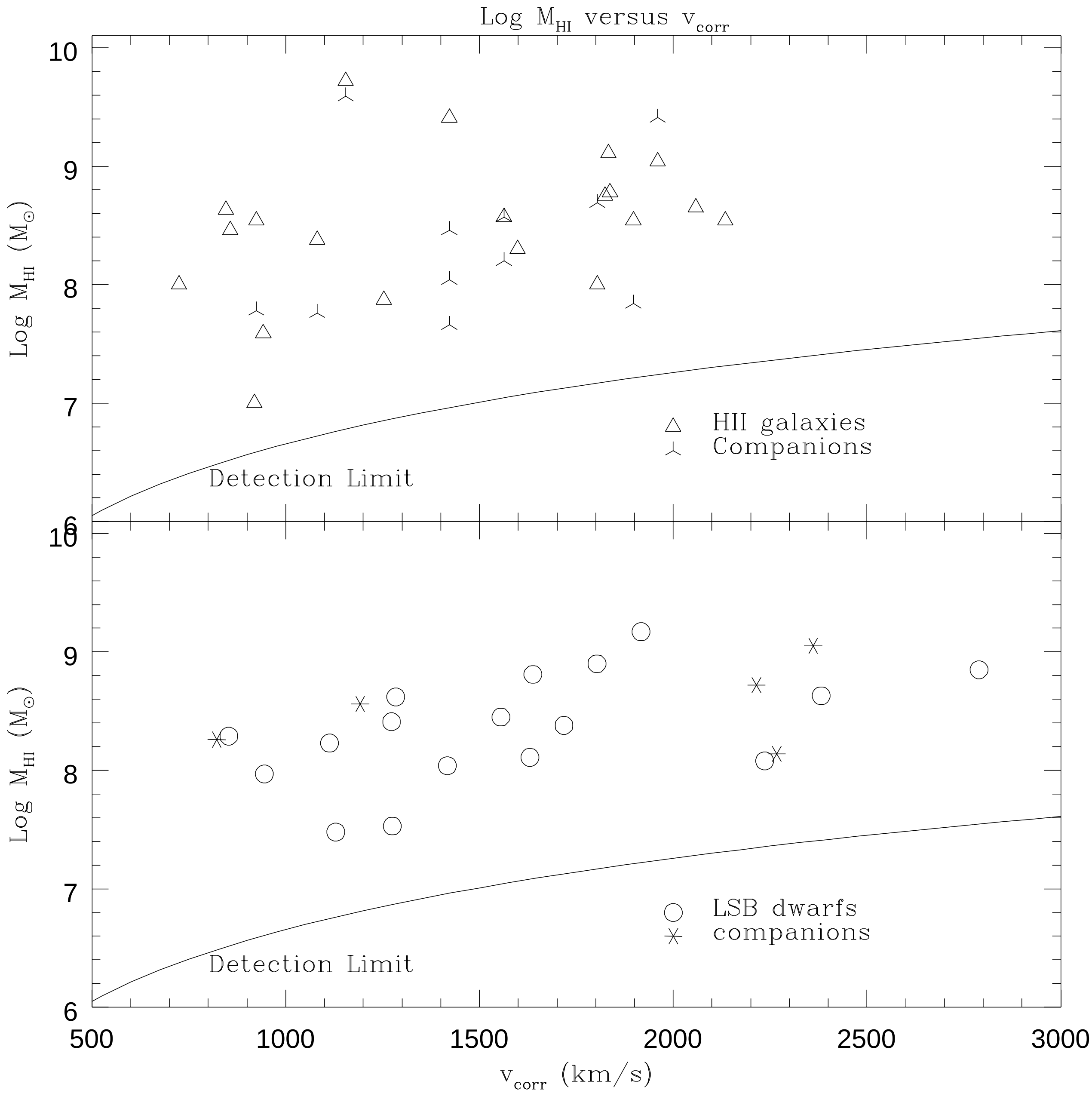
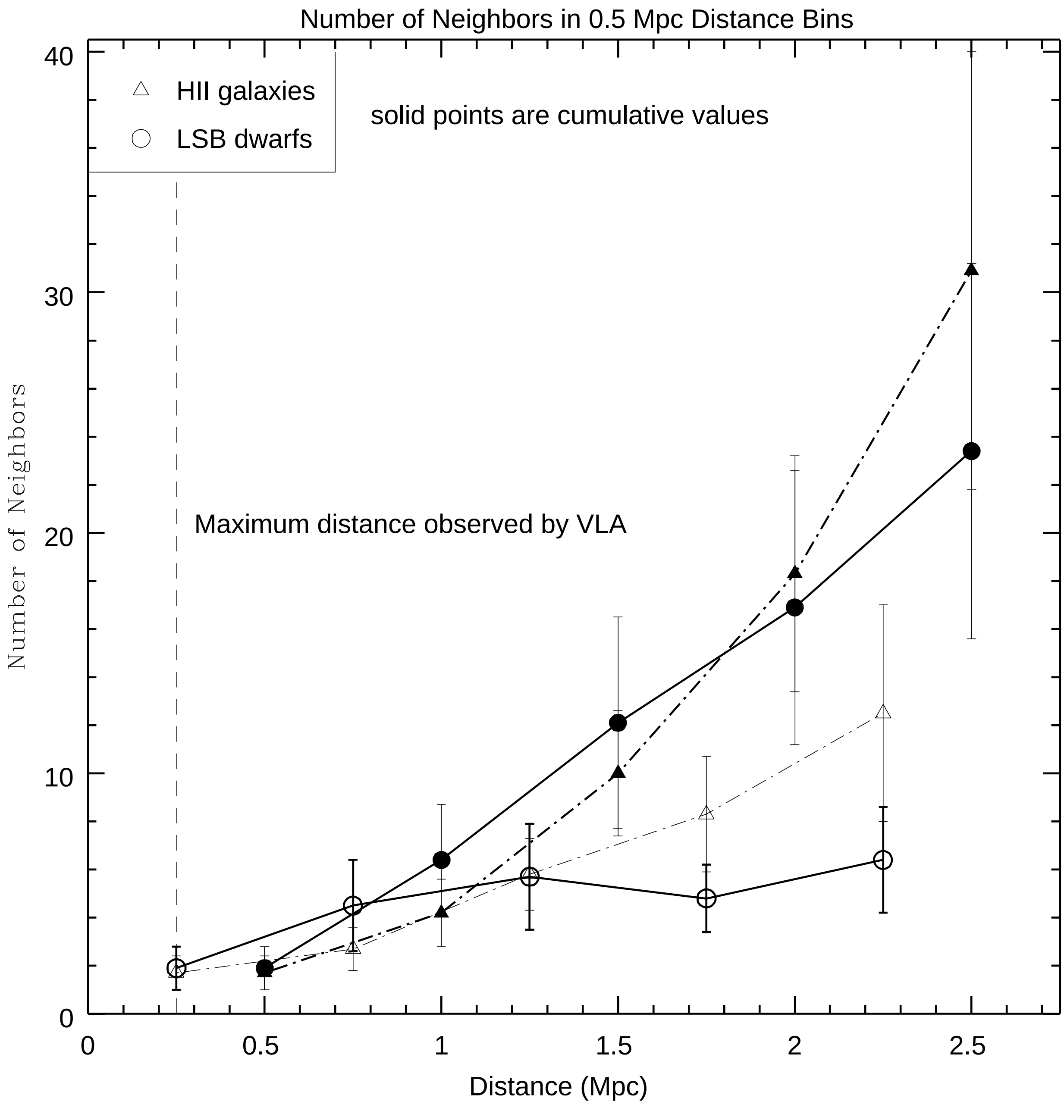

Log M_{HI} versus v_{corr}
Log M_{HI} ($M_\odot$)
HII galaxies
Companions
Detection Limit
LSB dwarfs
companions
Detection Limit
v_{corr} (km/s)
10
9
8
7
6
500
1000
1500
2000
2500
3000

Figure 5



Number of Neighbors in 0.5 Mpc Distance Bins
HII galaxies
LSB dwarfs
solid points are cumulative values
Maximum distance observed by VLA
Number of Neighbors
Distance (Mpc)
0
10
20
30
40
0
0.5
1
1.5
2
2.5

Figure 6